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Water Air Soil Pollut (2009) 196:141–149
DOI 10.1007/s11270-008-9763-3

Monitoring of Submicron Particulate Matter Concentrations in the Air of Turin City, Italy. Influence of Traffic-limitations

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Received: 15 January 2008 / Accepted: 25 May 2008 / Published online: 28 June 2008

Abstract Several studies have shown the association between ambient particulate matter (PM) and adverse health effects, thus highlighting the need to limit the anthropogenic sources of PM, especially motor vehicle emissions. PM exposure is commonly monitored as mass concentration of PM10 or PM2.5, although increasing toxicity with decreasing aerodynamic diameter has been reported. In the present study an analysis was performed of the concentration and size distribution of airborne PM fractions collected at street level in the city center of Turin, Italy, to verify the usefulness of "ecological" days with traffic limitations. PM levels were determined daily at five different outdoor sites, from Thursday to Tuesday for 7 weeks (five with "ecological" Sunday, two with normal traffic density). Air sampling was performed using a six-channel laser particle counter to determine the number of particles (n°/l) in six size ranges between 0.3 and 10 µm. Climatic conditions and indoor PM levels were also monitored. The PM size distribution was constant for all the samples tested, with the 90% of the particles smaller than 0.5 µm, suggesting that measurements for count are needed in addition to the traditional ones based on the mass. The total number of particles was highly variable comparing days or weeks of monitoring, but much less among the sites of air sampling. The restriction of motor vehicle circulation has not determined any significant effect on PM levels and, in the winter period, PM0.5 peak concentrations were measured also on the ecological days.

Keywords Air pollution · Human exposure · PM concentrations monitoring · PM size distribution · PM toxicity · Submicron particulate matter

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1 Introduction

The airborne particulate matter (PM) comprises a wide range of particles suspended in the atmosphere, with aerodynamic diameter up to 10 µm (PM10). About 85% of atmospheric particles originates from anthropogenic sources including burning of coal, oil, natural gas, wood and other biomasses; and, especially, internal combustion engines and heat or power plants (Council of Europe 1998; Wilson et al. 2002; Artiñano et al. 2003). The chemical composition of

PM is extremely heterogeneous and many researchers have demonstrated the usefulness of separating the particles in at least three or four categories on the basis of their mean size: coarse (PM10), fine (PM2.5), submicron (PM1.0) and ultrafine (PM0.1) (Wilson et al. 2002; Englert 2004).

Several epidemiological and toxicological studies have shown the association between PM and adverse health effects such as respiratory diseases (chronic bronchitis, aggravation of asthma), cardiovascular pathologies and pulmonary tumours (Saldiva et al. 2002; Pope et al. 2004; Kappos et al. 2004; Dockery and Stone 2007). These effects are thought to arise from the possibility of inhaling heavy metals, polyaromatic hydrocarbons, radical species, endotoxins, viruses/bacteria, etc. in combination with the particle matrix (Pakkanen et al. 2001; Okeson et al. 2003).

The impact of airborne particulates on human health depends on many factors, including particulate mass, size distribution and composition. PM exposure is commonly monitored as mass concentration of PM10 or PM2.5. However, according to various authors, toxicity is bound to the dimensions of the particles because of deposition issues (Okeson et al. 2003), and increasing toxicity with decreasing aerodynamic diameter has been reported (Smith et al. 2000). During inhalation, particle size will influence in what region of the airways the material will be deposited (Granum and Løvik 2002). The coarse PM is easily retained in the first aerial ways; while fine–ultrafine particles can penetrate deeper into the lungs, deposit in the alveolar region and may also be transported via the blood stream to other tissues and organs, such as the heart (McClellan, 2002). Furthermore, the fine particulate fraction formed through the process of fossil-fuel combustion contains the most toxic components of the particles (organics, ammonium, sulphates and nitrates), providing a biologically plausible mechanism for causality (NJ Clean Air Council 1997). For all these reasons, small PM can induce stronger adverse effects and is thus considered more dangerous to human health than larger particles composed of the same material (Dellinger et al. 2001). The available evidence suggests that pathogenic mechanisms may be linked to the number (or total surface area) of particles inhaled and retained in the alveolar ducts rather than to the total mass of the material.

Particle mass, strongly influenced by large particles, is actually a poor indicator for the amount of the small PM (Nygaard et al. 2004). Moreover, even though the potential toxicity of coarse particles should not be neglected (Brunekreef and Forsberg 2005; Schwarze et al. 2007), the particles at the largest end of the size range tend to have short suspension times (hours) and rapidly fall out of the atmosphere. In contrast, submicron and ultrafine PM can remain suspended in the ambient air for days to weeks and can be carried over large distances (Granum and Løvik 2002; Armaroli and Po 2003).

The spatial and temporal distribution of airborne PM concentrations is also influenced by meteorological factors such as air pressure, temperature and humidity, precipitations and winds (Olcese and Toselli 1998). Rain tends to remove pollutants from the atmosphere; while wind currents can mobilize, resuspend and transport the particles very far from the source (Armaroli and Po 2003).

Among the pollutants regulated by the European community, PM is one of those which more frequently exceeds the limit values. According to the European Union Directive on particulate matter (1999/30/EC), PM10 values must not exceed the yearly average limit of 40 μg/m^3 or daily average of 50 μg/m^3 on more than 35 times per year. Both values are already frequently exceeded in European cities, especially in streets and other urban hotspots. The projections for 2030 suggest that the PM10 limit value is not expected to be met even in the most optimistic scenario (EEA 2006).

Many Italian cities and towns are affected by high levels of PM, which calls for measures to limit their anthropogenic emission; especially fuel combustion from motor vehicular traffic which is the main source of fine–ultrafine particles. In Turin (Torino, northwestern Italy, population 900,000), the PM limit has been exceeded on 166 and 202 in 2004 and 2005, respectively. To protect the population, the most common, albeit unpopular, measure from local authorities consists in traffic-limitations (including road closures in the city center and/or restrictions on the circulation of old, non-catalyzed vehicles). Such measures are generally implemented on Sundays and are advertised as “ecological Sundays”.

2 Aims

The main goal of this study was to evaluate the usefulness on air PM pollution of the restrictions to the motor vehicular traffic during "ecological" days in the period April 2004–February 2005.

An analysis was performed of the numerical concentration and size distribution of the dimensional airborne PM classes, collected at the street level in the city center of Turin, Italy, focusing the attention on submicron particles (PM0.5). Data on PM concentration at the various sampling sites (inside or outside of the traffic-restricted area), indoor PM levels and meteorological influences are presented.

The available results also allow to determine the dimensional distribution of particles and the PM levels people undergo in Turin city during different periods of the year. The practical implications of our findings for the local monitoring and health protection strategies are briefly discussed.

3 Materials and Methods

3.1 Instruments

Air sampling of ambient particulates was performed using a six-channel laser particle counter (ParticleScan Pro, IQAir®, USA) to determine the number of particles per liter in six size ranges between 0.3 and 10 μm: >0.3, >0.5, >0.7, >1.0, >3.0 and >5.0 μm.

The main instrument specifications were: laser source diode 680 nm, minimum sensibility 0.3 μm, flow rate 0.01 cfm. The particle counter was connected to a Windows®-based laptop and PM data acquired by Microsoft Excel® software.

Climatic condition were monitored using a barometer-hygro-thermometer weather station (Tip Weather Station®, Oregon Scientific, Inc., USA), wind gauge (Windmaster 2®, Kaindl Electronic, Germany), and rain gauge consisting in a neoprene funnel with an opening of 24 cm and a surface of 452 cm^2, a manifold pipe and a graduated cylinder of collection with suitable volume.

3.2 Sampling

On "ecological days", typically Sundays, vehicles' circulation in the traffic-limited zone ("ZTL"—Zona a Traffico Limitato) of the city center of Turin was restricted from 10:00 A.M. to 7:00 P.M. A map of the ZTL, an area of 1.03 km^2 with 12,500 inhabitants, is shown in Fig. 1.

The restriction applied to diesel and gasoline vehicles; albeit with many exceptions for public transport, emergency and operative vehicles, etc. The decrease of the vehicular traffic was 18,000 vehicle passages (data from local traffic office) corresponding to about 30–40% of the mean daily traffic volume.

PM levels were determined daily at five different outdoor monitoring stations (A–E): two of them inside the ZTL area and the others located at the margins of the ZTL where the circulation of the vehicles was unrestricted and the traffic concentrated (Fig. 1). Air sampling was performed at 1–1.5 m above ground level to directly simulate the individual's breathing zone.

Samples were collected from Thursday to Tuesday (6 days) of 7 weeks in the period April 2004–February 2005 (Table 1). For each day, PM levels were expressed as mean and standard deviation (SD) of 10 replicate measurements performed between 7.00 and 8.00 P.M.; i.e., at the end of the traffic-limitation period. Weeks 1 to 5 were planned with traffic-limitation (ecological Sundays), while no limitations were enforced (normal traffic density) in weeks 6 and 7 (Table 1).

Indoor PM values were measured once per week (on Thursdays) inside the buildings of the University of Turin, as a simple instrumental check preceding each series of measurements and preliminary investigation of the relationship between indoor and outdoor air particles concentrations.

4 Results

We collected a total of 188 airborne PM samples distributed among five outdoor sites during 40 non-consecutive days (Table 1) accompanied by seven indoor determinations, once per week. Data collection was occasionally prevented due to technical problems or road closures. Official PM10 data from regional air quality authorities ("ARPA Piemonte") for the same period, measured using gravimetric methods (μg/m^3), are reported in Table 2 for comparison and discussion purposes.

On a percentage basis, the size distribution of airborne particulate matter was extremely stable in all samples, regardless of the total number of particles. As shown in Table 3, PM0.5 accounted for about the

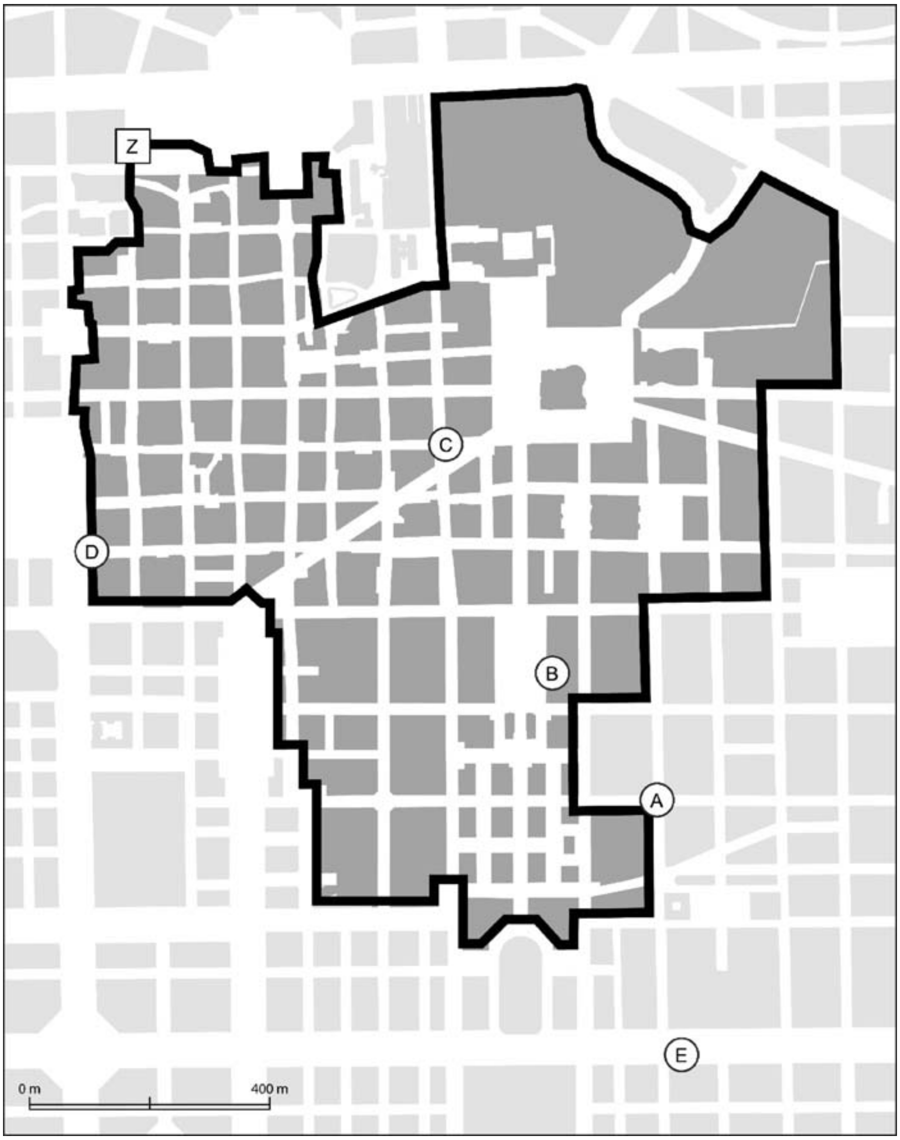

Fig. 1 Map of the city center of Turin, with the area subjected to traffic limitations ("ZTL", in *gray with black borders*). *A–E* are the locations of air sampling sites used in the study; *Z* is the site of monitoring by regional air quality authorities

92% of total PM. This stable size distribution of ambient PM of Turin city was observed both for outdoor and indoor samples.

On the contrary, the measured PM0.5 levels (expressed as number of particles per liter of air) showed a high temporal variability both between weeks and/or among the days during each week (Fig. 2). For this reason, we could not highlight any overall trend in PM0.5 levels from Thursday to Tuesday, although the traffic, in general, tends to decrease during the weekend. The average increase of PM0.5 outdoor levels, compared with the corresponding indoor values, was about 50–100%.

As expected, PM0.5 peak concentrations (over 500,000 particles per liter of air) were measured in the winter season, also during the ecological days.

Contrary to the temporal variability, the number of PM0.5 particles did not vary significantly among the monitoring stations inside or outside the traffic-limitation area (CV mean 23%, CV range 4–52%, Table 4).

The data collected during ecological weeks did not show any generalized and significant improvement derived by the traffic-limitation on Sunday, with the exception of weeks 2 (May 13–18, 2004) and 5 (November 4–9, 2004, Fig. 2). Moreover, the percent-

Table 1 Samples collection and main meteorological conditions

Week	Period	Traffic-limitation	Notes about main meteorological condition
1	April 15–20, 2004	Yes	T: 11–21°C—H: 35–80%—Wind on day 18 (2 m/s) Rain on days 16 (7 mm), 17 (20 mm) and 19 (12 mm)
2	May 13–18, 2004	Yes	Temperature: 16–26°C—Humidity: 31–54% Wind on day 14 (2 m/s)
3	June 3–8, 2004	Yes	Temperature: 24–29°C—Humidity: 31–42%
4	September 23–28, 2004	Yes	Temperature: 21–28°C—Humidity: 25–38%
5	November 4–9, 2004	Yes	Temperature: 17–23°C—Humidity: 34–63% Wind on day 9 (4–6 m/s)
6	July 1–6, 2004	No	Temperature: 20–29°C—Humidity: 21–60%
7	February 17–22, 2005	No	Temperature: 11–16°C—Humidity: 27–45%

age distribution of the PM and the numerical PM0.5 concentration levels during the two weeks without restriction of the vehicular traffic were comparable with the weeks with ecological Sunday (Fig. 3).

As reported in Table 1, rainy days (7–20 mm) occurred only on three occasions (week 1, April) during the study period and the presence of a wind speed over 2 m/s was an unusual condition in our city. Due to these small data sets a statistical analysis was not possible, even if precipitations and wind can affect the pollution from microdusts.

5 Discussion and Conclusions

Many cities and towns worldwide are affected by high levels of air particles and, in the recent years, several researches have studied PM levels and composition in various urban and rural areas using different sampling techniques (Pakkanen et al. 2001; Wilson et al. 2002; Artiñano et al. 2003; Kappos et al. 2004). Most researchers usually express particle concentrations in terms of particle mass-weight per volume units of air (μg/m^3, gravimetric methods). However, PM is very heterogeneous and consists of particles varying in size, shape, and specific weight (Granum and Løvik 2002). Often, the levels measured at the same monitoring sites using different methods are not well correlated with each other, and there is limited information on how well ambient monitoring reflects human exposure to PM (O'Neill et al. 2004).

Moreover, the overall number of particles smaller than 10 μm is dominated by the finest particles, the most dangerous to human health, whereas most of the PM mass is concentrated in large particles (Granum and Løvik 2002; Armaroli and Po 2003). Gravimetric analysis (normally used in official monitoring programs) is strongly influenced by large particles and therefore is a poor measure for characterizing the amount of the small PM (Nygaard et al. 2004). The determinations of PM size composition and particle numbers concentrations are more relevant parameters

Table 2 PM10 gravimetric determinations (μg/m^3) in the urban center of Turin city; data from regional air quality authorities (daily mean of the 24 h)

Week	Period	Day of sampling[a]					
		Th	Fr	Sa	Su	Mo	Tu
1	April 15–20, 2004	40	11	22	33	13	29
2	May 13–18, 2004	32	29	40	29	34	76
3	June 3–8, 2004	27	26	26	21	26	29
4	September 23–28, 2004	52	41	30	22	42	65
5	November 4–9, 2004	89	103	109	49	46	44
6	July 1–6, 2004	58	42	30	41	52	50
7	February 17–22, 2005	55	75	90	87	38	79

[a] Day of sampling, from Thursday to Tuesday of each week (Th–Tu)

Table 3 Particle counts and PM percent size distribution

Ø μm	PM10 (total)	<0.5 (0.3–0.5)	0.5–0.7	0.7–1.0	1.0–3.0	3.0–5.0	>5.0 (5.0–10)
Mean (n°/l)	185,540	169,020	12,357	2,751	971	375	66
%	100	92.3	5.4	1.3	0.6	0.3	0.1
SD %	–	2.8	1.9	0.7	0.4	0.3	0.1
CV %	–	3	35	53	63	93	146

Number of particles per liter of air (n°/l)—mean values, standard deviation (SD) and coefficient of variation (CV, relative standard error) of 195 samples collection

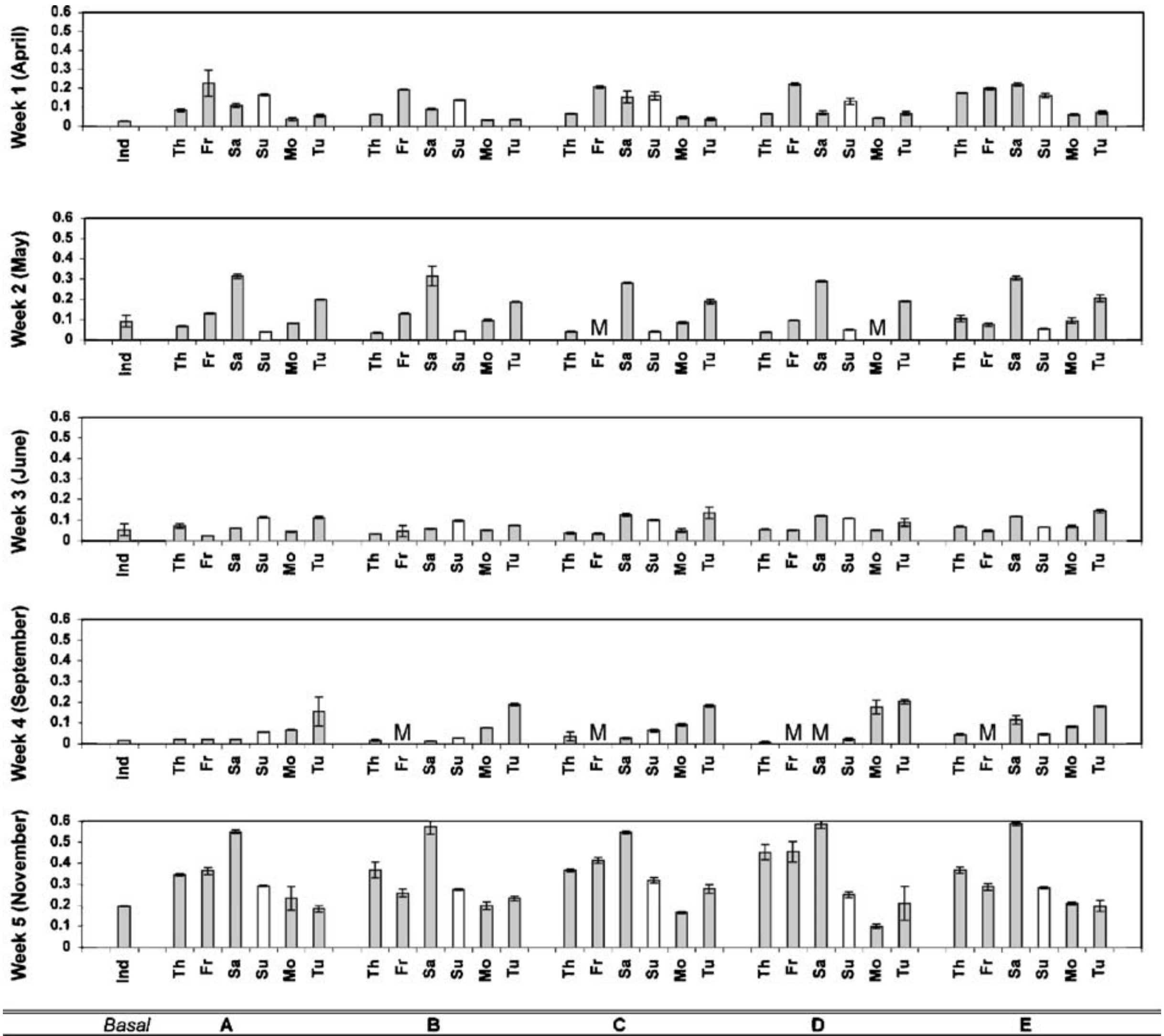

Fig. 2 PM0.5 levels in weeks with traffic-limitation on Sunday. Total number of PM <0.5 μm per liter of air (millions of particles), measured in five city-locations (*A–E*) from Thursday to Tuesday (Th–Tu). Means±standard deviation values. Legend: *Ind*=indoor PM0.5 levels; *white bars*=PM0.5 levels on Sunday; *M*=missing data

Table 4 Coefficient of variation in percent comparing the five PM sampling sites (A–E)

Week	Period	Day of sampling[a]					
		Th	Fr	Sa	Su	Mo	Tu
1	April 15–20, 2004	52	7	47	10	26	41
2	May 13–18, 2004	45	24	5	14	8	4
3	June 3–8, 2004	32	29	34	18	18	27
4	September 23–28, 2004	45	M	37	42	45	13
5	November 4–9, 2004	11	23	4	9	29	17
6	July 1–6, 2004	48	37	8	M	M	31
7	February 17–22, 2005	13	13	5	9	4	13

[a] Day of sampling, from Thursday to Tuesday of each week (Th–Tu); *M* missing data

to human health (Penttinen et al. 2001) and should be considered in the development of future monitoring strategies.

In the present study, we performed, for the first time in the city of Turin, a numerical determination of airborne PM, with the goal to directly evaluate the potential exposure of the population to particles and the possible benefits derived by the restrictions to the motor vehicular traffic. Our data cannot inform about global values during the 24 h, but are "pollution snapshots", taken in the late afternoon of particular periods (ecological weeks), of PM levels people may inhale in the streets of the city center of Turin.

Our results confirm the importance of measuring particles' number instead of their mass and show that, on a number basis, submicron particles (PM0.5) constitute over 90% of the airborne particulate matter monitored in our city. In addition, the dimensional-based distribution of PM turns out to be extremely stable regardless of the number of particles and this trend is confirmed both for the outdoor and the indoor air sampling sites. Particle concentration counts inside the buildings, in the absence of indoor sources, are usually lower than outdoor values (Franck et al. 2006). Our findings conformed to this trend, although we observed a relationship between inside and outside values due to the continuous "to and from" air exchange between indoor and outdoor compartments.

For PM0.5, peak concentrations over 500,000 particles per liter of air were measured in the cold season (weeks 5 and 7; see Table 1 and Figs. 1 and 2), also in correspondence with the ecological days. These findings would point to residential heating and power plant emissions as the main anthropogenic PM sources for the city of Turin. The winter period augmentation in traffic volume cannot in fact explain the observed two- three-fold increase in PM levels.

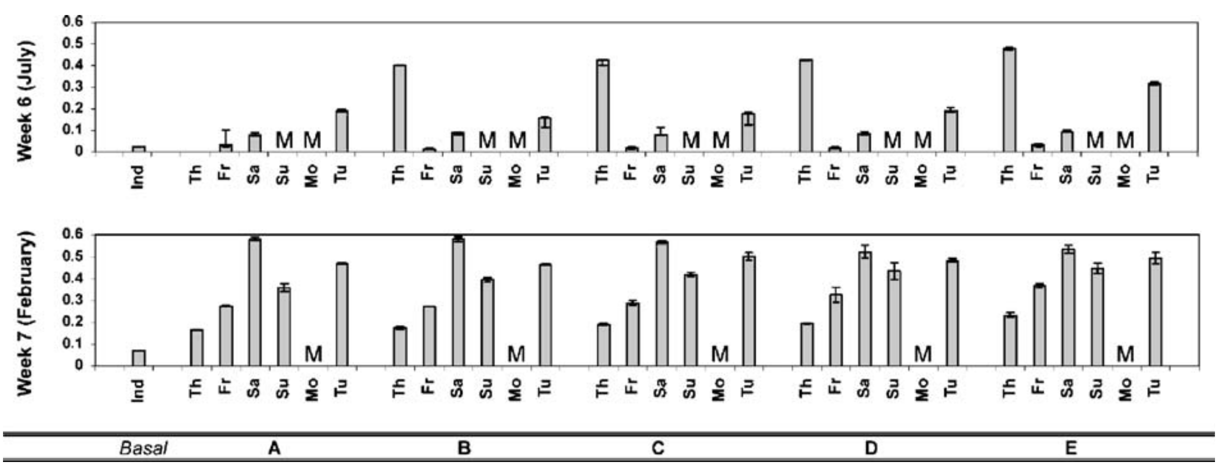

Fig. 3 PM0.5 levels with normal motor vehicles circulation. Total number of PM <0.5 μm per liter of air (millions of particles), measured in five city-locations (*A–E*) from Thursday to Tuesday (*Th–Tu*). Means±standard deviation values. Legend: *Ind*=indoor PM0.5 levels; *M*=missing data

Contrary to our data (Figs. 2 and 3), PM10 mass concentrations (Table 2) occasionally exhibited large differences between November and February despite the similar climatic conditions. Temperature conditions during November sampling were actually unusually mild for the season and in comparison with the mean values of that month's in our city (min 2°C, max 11°C). Overall emissions from residential heating were therefore probably higher in November than in February; which would account for the peak PM10 mass concentrations in November. At the same time, the unexpected and temporary temperature increase in November caused the drop in PM10 during the second part of the sampling period. These considerations are very instructive in showing that reliance on PM10 mass measurements (strongly influenced by large particles) can easily lead to an underestimation of actual health risk. On the other hand, PM0.5 particle counts (based on particles with long atmospheric residence times) are much less affected by short-term events and climatic fluctuations.

The potential impact on human health due to such a great number of small particles can be estimated by some simple calculations. An average adult breathes about 500 l of air per hour; that is he/she inhales up to 2.5×10^8 (500,000·500) particles per hour at street level. Children are still more exposed, because their respiratory systems are still developing and they breathe even more air per kilogram of body mass than adults.

Given these PM figures and considering a healthy individual with normal pulmonary ventilation, less than one alveolus out of one thousand comes into contact with a "coarse" 5–10 μm particle (0.1% of PM10 size composition and easily kept by the first aerial ways) on a daily basis. On the other hand, a typical alveolus would be reached by hundreds of PM0.5 particles which are able to penetrate the epithelium and cause adverse effects. Children are especially vulnerable and the inhalation of fine particles is considered one of the reasons of the increasing diffusion or exacerbation of asthma; the most common chronic illness in children (Schwartz 2004; Sun et al. 2006).

The determinations we performed in the city center, during six days of observation per week, did not show any generalized and significant benefit on the PM0.5 levels derived by the Sunday traffic-limitation. We also verified quite stable PM0.5 numbers of particles among the five outdoor sampling sites, without significant disparities among monitoring stations inside or outside the restricted area.

These results are consistent with previous evidence of a relationship among particle size, air persistence and capability to be transported over long distances. According to Armaroli and Po (2003), the air PM persistence increases from few hours to weeks from coarse to ultrafine particles respectively, with an intermediate behavior for the fine PM. The lifetime of small particles in the atmosphere is therefore very long and they can travel thousands of kilometres by air currents. Most urban and other densely populated areas are covered by a widespread, fine-particle pollution haze which can extend over hundreds of kilometres (Council of Europe 1998). Based on these considerations, the temporal pattern for PM levels in cities would not reflect road closures and local traffic, but is more likely associated with the effects of mid- and long-range atmospheric transport (Levy et al. 2006).

Thus, a possible explanation of our data is that the degree of air PM pollution in the center of Turin can be supported and partially preserved by the traffic persisting in the surrounding areas despite the localized restrictions of motor vehicle circulation. Based on this hypothesis, an enlargement of the restricted circulation area (and especially long-term plans to encourage a more environmental-friendly mobility) would be much more useful than frequent or severe traffic-limitations, in order to try to reduce the PM pollution in our city. A new, improved, and expanded air quality monitoring plan will also be necessary to ensure an effective pollution abatement and protection of citizens' health.

Acknowledgements This study was supported by a grant of the Piedmont Regional Government, Italy (Regione Piemonte, Bando 2003).

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